Gamma-rays and Radioactive Isotopes

Chris Fryer (LANL)

Why do we care about radioactive isotopes?

How can gamma-ray observations help?

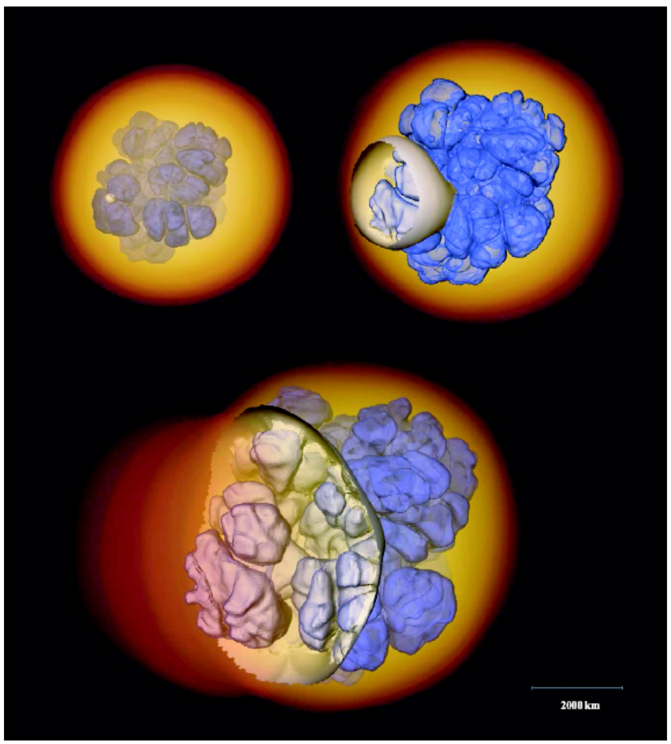
What is nuclear astrophysics anyway?

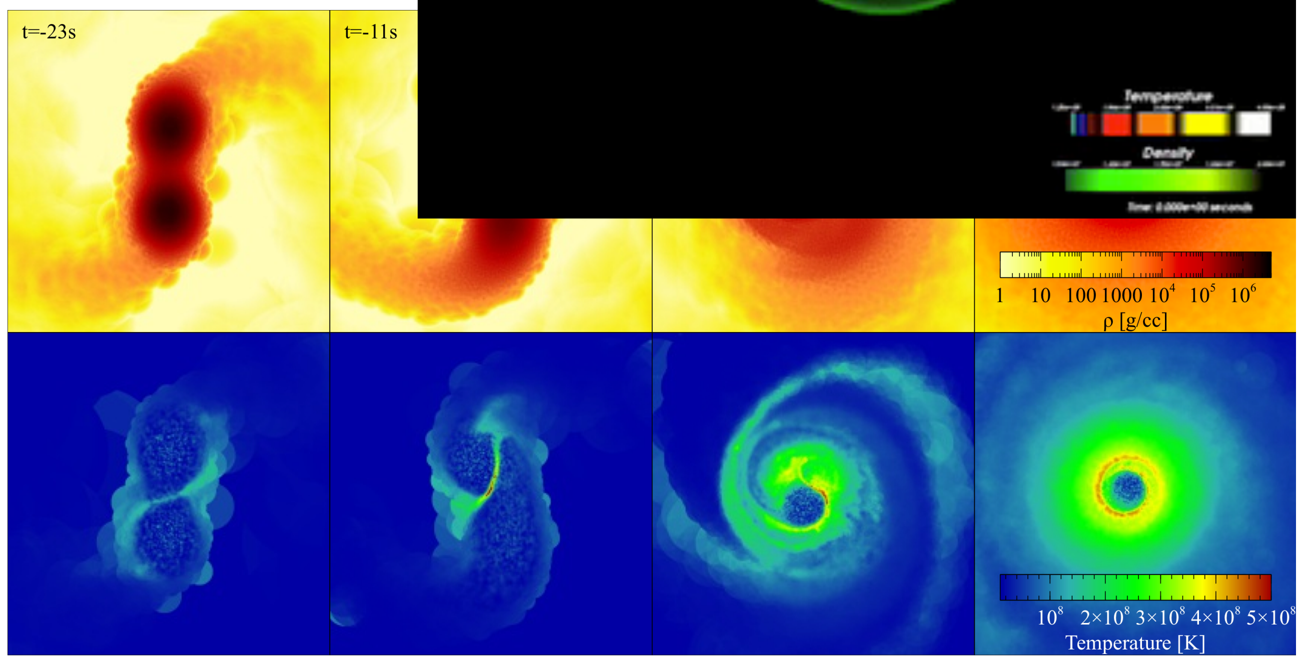
Why do we care?

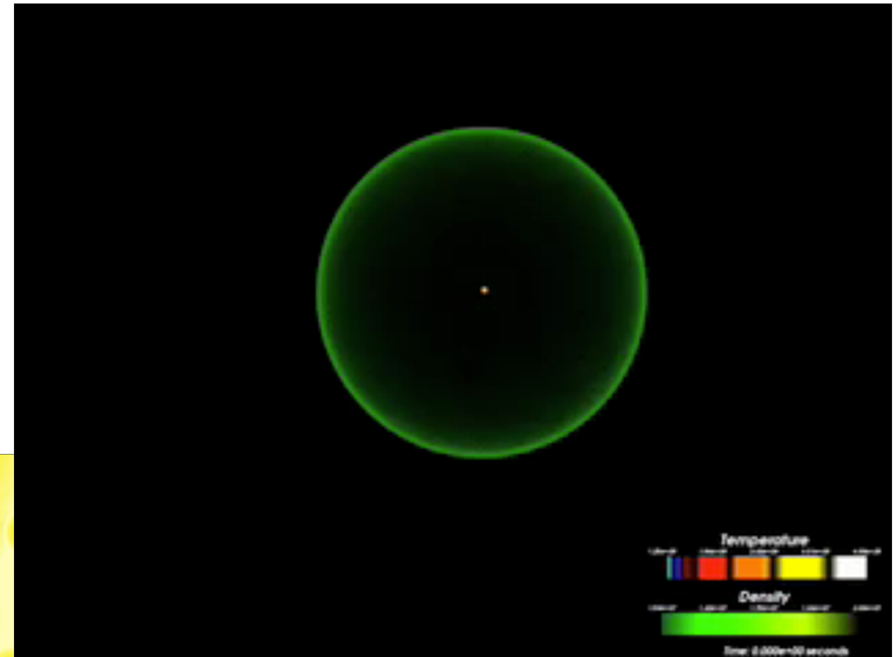
- Radioactive elements provide a unique probe to study the engines of both thermonuclear core-collapse supernovae, avoiding many of the analysis errors of other elements produced in these explosions.
- Long-lived isotopes provide an alternate guide of the star formation in the Milky Way (and in specific star forming regions).
- These long-lived isotopes also have the potential to allow us to probe remnant evolution.
- With upcoming nuclear physics laboratories, we are at the beginning of a revolution in nuclear astrophysics.

Thermonuclear Supernova

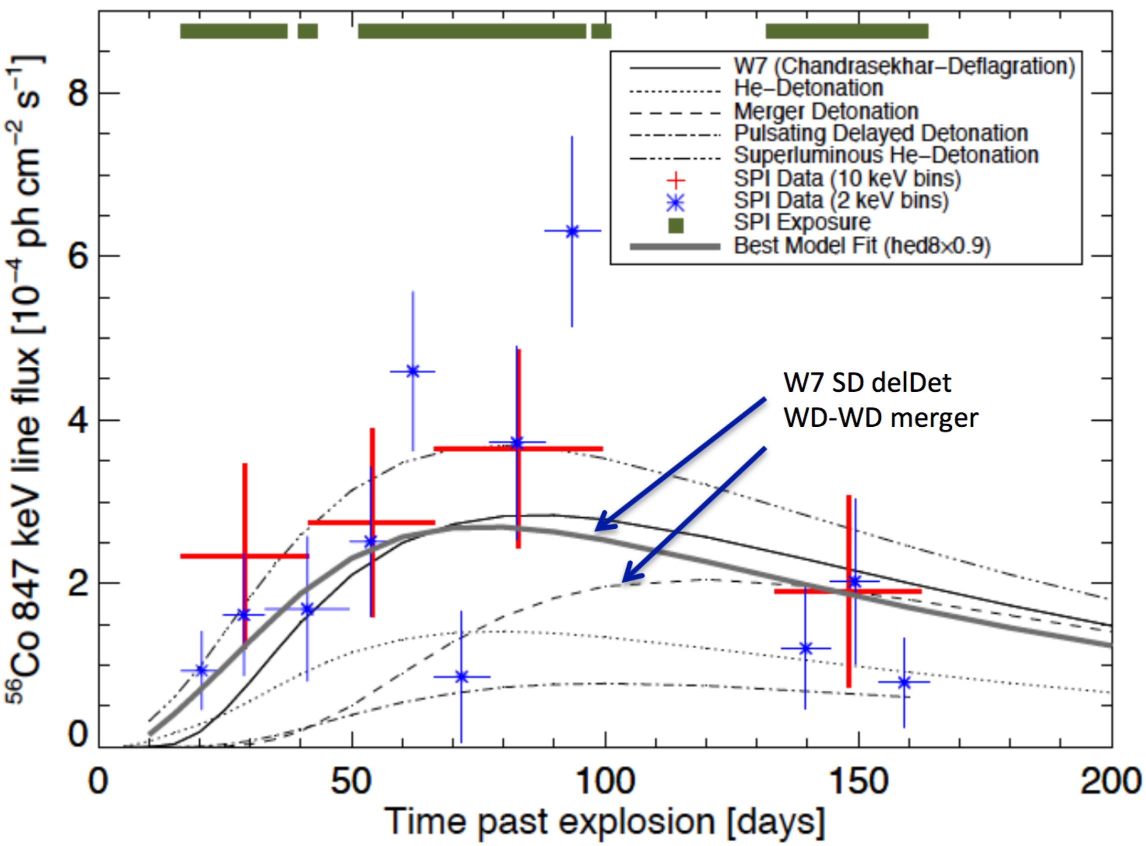
- Lots of engines and progenitors: deflagration, deflagration to detonation, gravitational confined detonation, merger, …
- Models predict different distributions for the ^{56}Ni. By observing the gamma-rays, we can probe this distribution.







Thermonuclear Supernovae

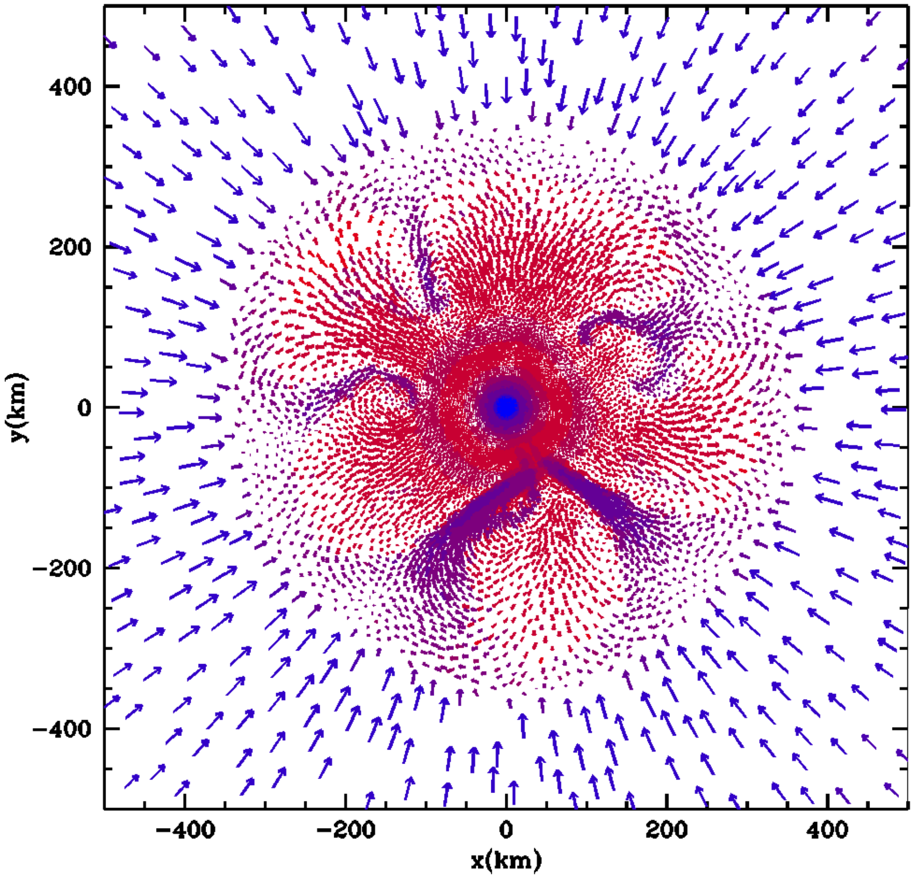


Theorists are building a better understanding of the correlation between LCs and gamma-rays!

- Understanding TN SNe critical to reduce systematics in these probes of the early universe (empirical methods have trouble calibrating against evolutionary differences).
- ^{56}Ni production is at the heart of understanding any thermonuclear supernova engine. Gamma-rays probe the production of ^{56}Ni in Thermonuclear Supernovae.
- Gamma-rays can provide the spatial distribution of the ^{56}Ni either by time-dependence or energy resolution.
- Next generation detectors could observe 10-100 events/year. will provide the first understanding of the explosion mechanism(s) for type Ia supernovae.

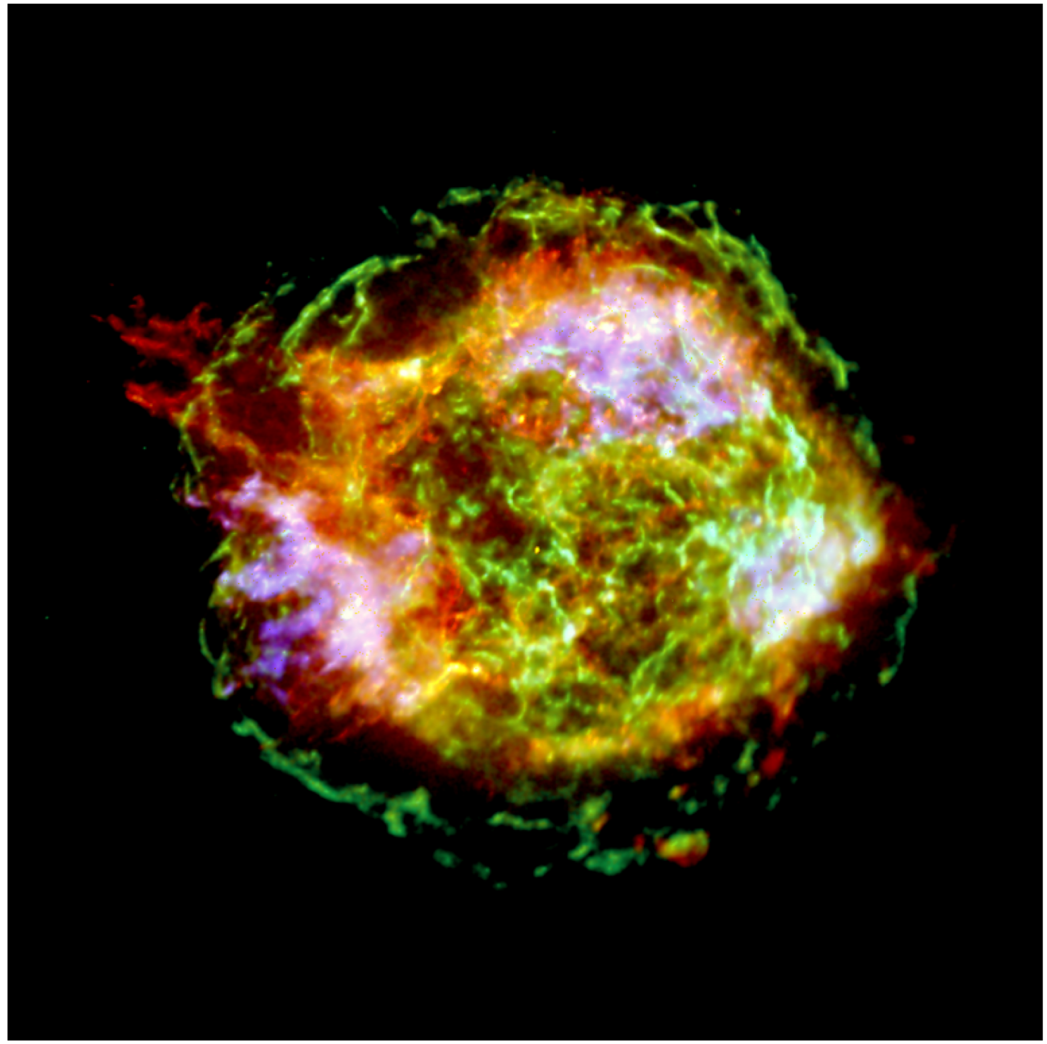
Core-Collapse SNe

- Convective Supernova Engine
- Needed an explanation for the early rise of gamma-rays in SN 1987A.
- Naturally explained how most supernovae are 1 foe (even though 100 foe is released in collapse)
- Predicted range of NS masses, SNe produced from lower mass, massive stars, …
- But is it the engine?

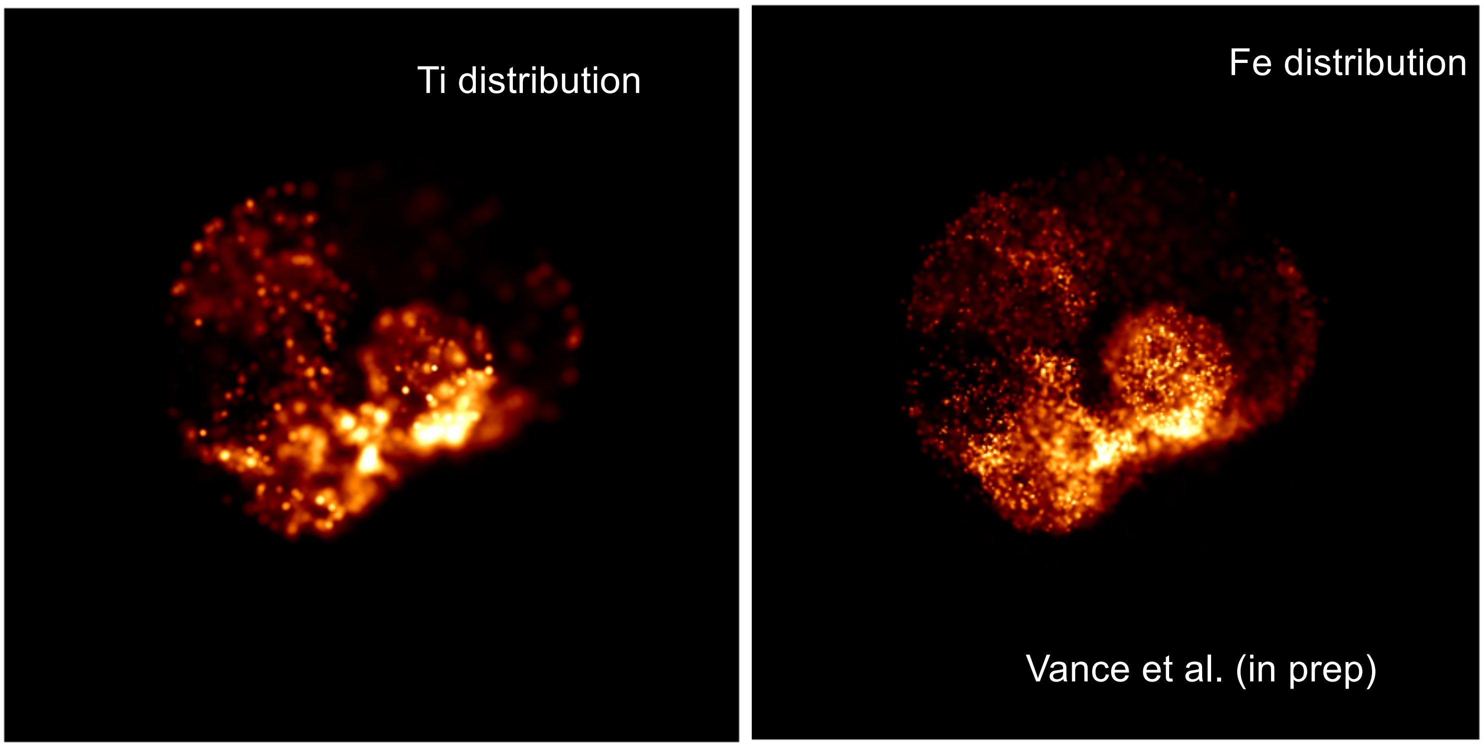


Cassiopeia A

- Observations of Cas A from shock heated elements painted a jet-like picture.
- Theorists argued that this “jet” was an artifact of asymmetric surroundings, but many in the community believed (and some still believe) that this jet argued for a GRB origin of Cas A.
- However, shock-heated elements do not trace the full explosion, just the elements that are shock heated.

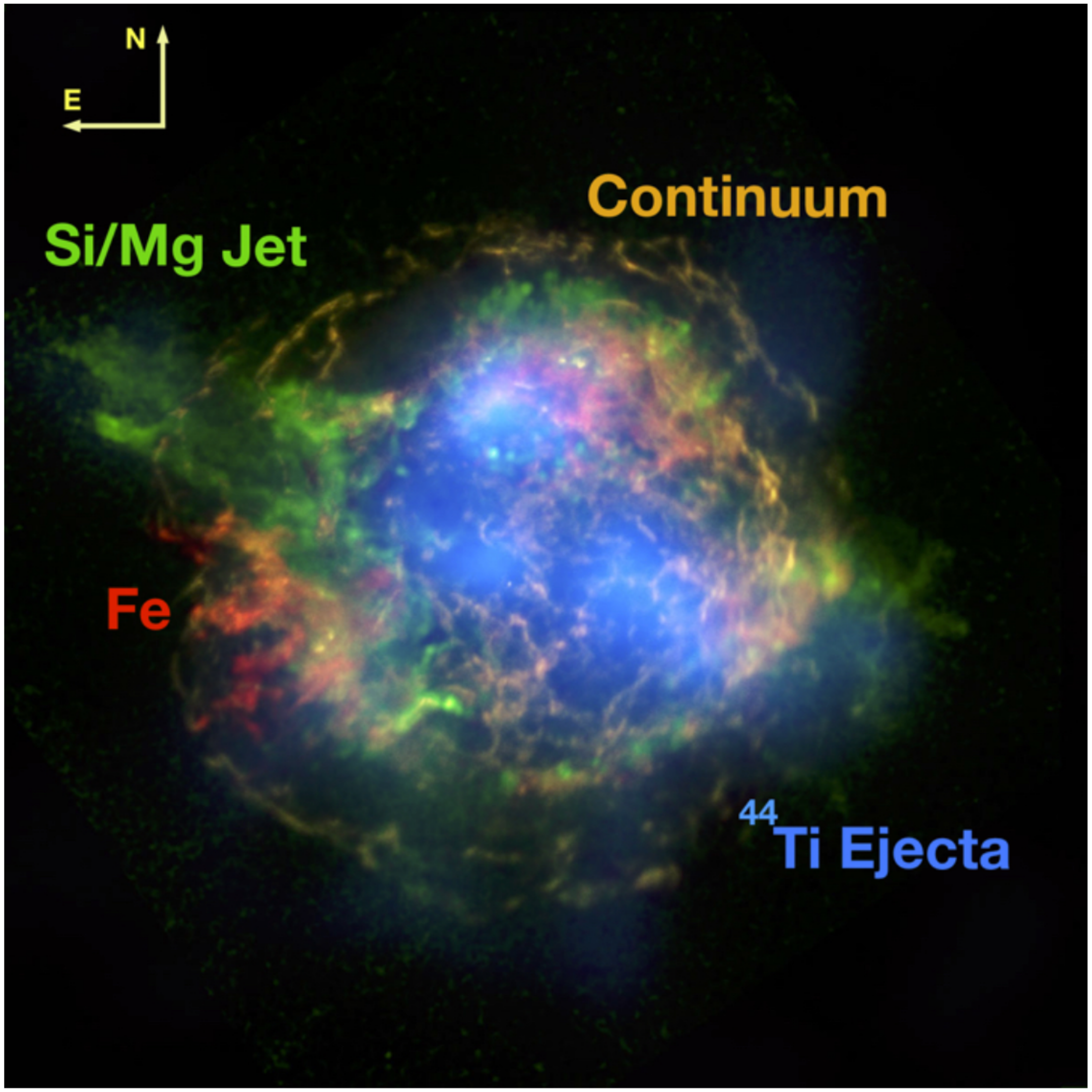


^{44}Ti is produced in the innermost ejecta with the iron. The convective supernova engine predicts a ^{44}Ti distribution mimicking the convective flows.



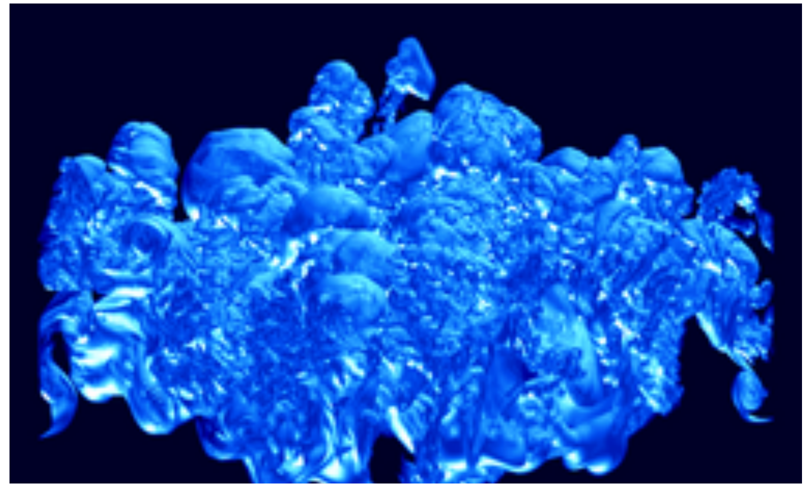
Core-collapse Supernovae and Cas A

- Hard X–ray decay lines of ^{44}Ti showed that the engine was not a jet, but something like the convective engine (with "lobes" of ejecta). This is the best support to date for the supernova engine developed by theorists!
- With more data, we can probe this engine more completely.



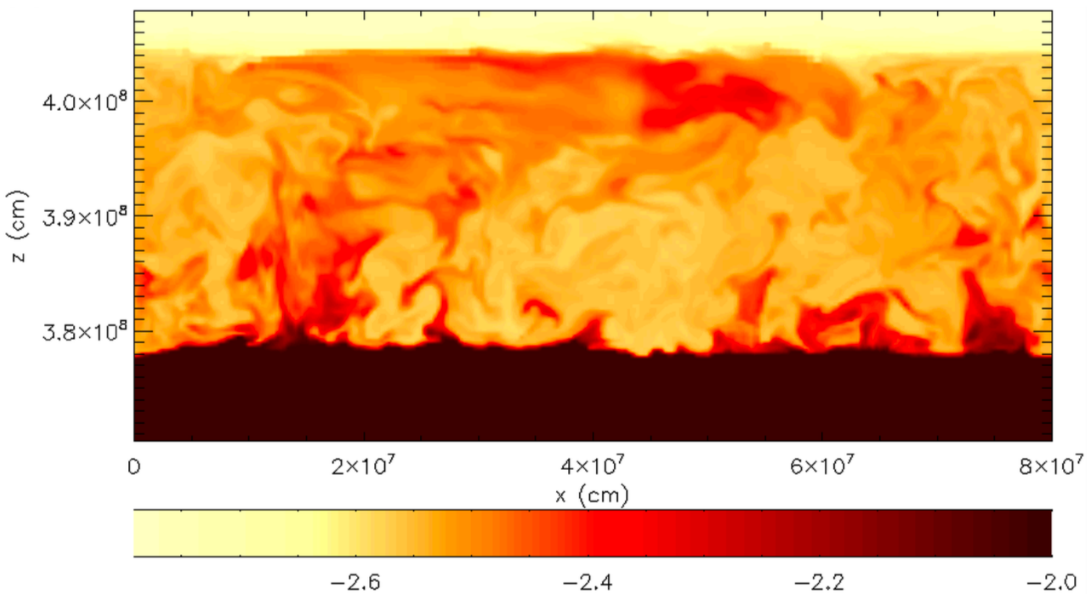
Novae

- Mass ejection from Novae determines how easily we can accrete onto WDs (and hence make TN SN progenitors).
- Nova Probes include e^+ from ^{13}N and ^{18}F and the decay of ^{7}Be and ^{22}Na
- Next generation telescopes will allow systematic, time-domain studies of Novae.



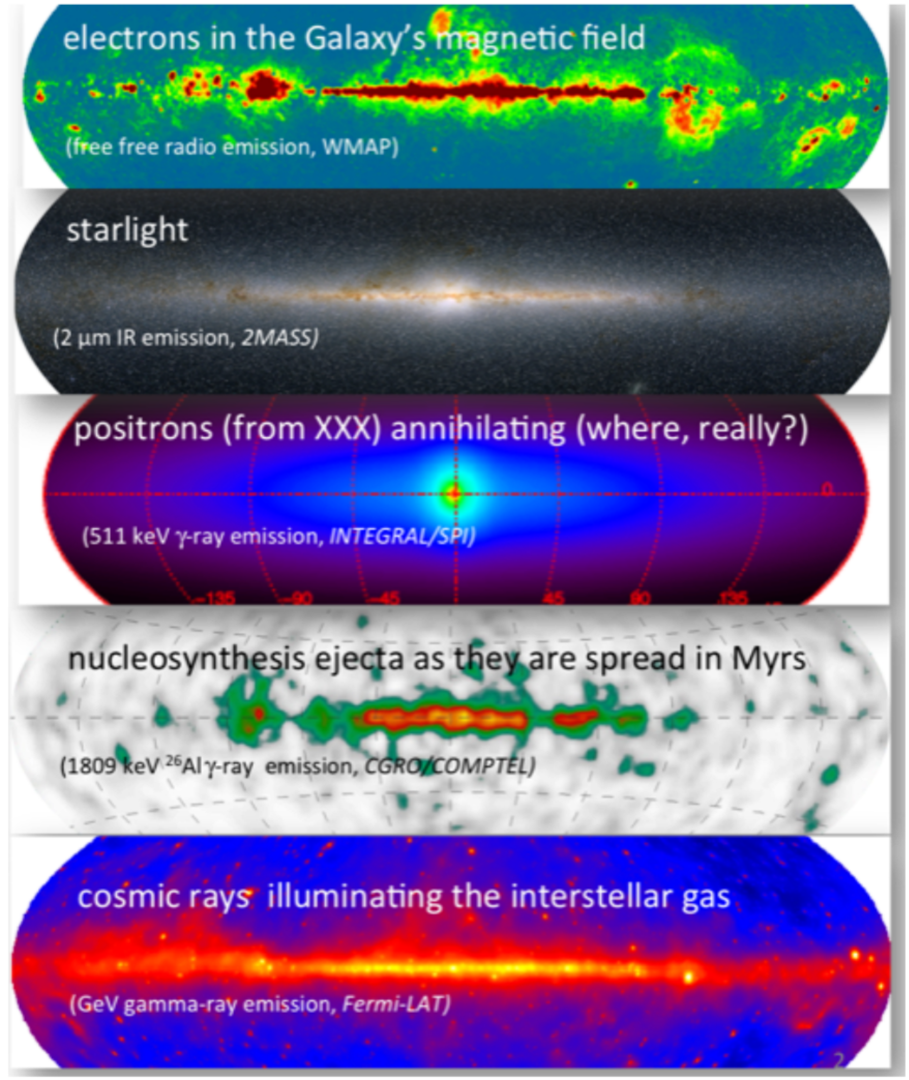
Zingale

Casanova et al. 2016

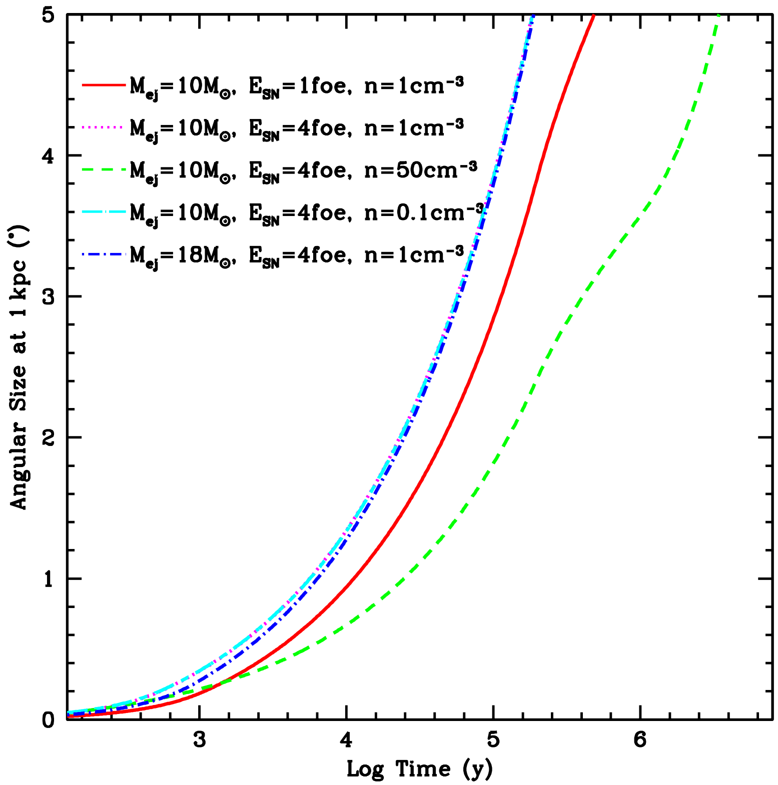


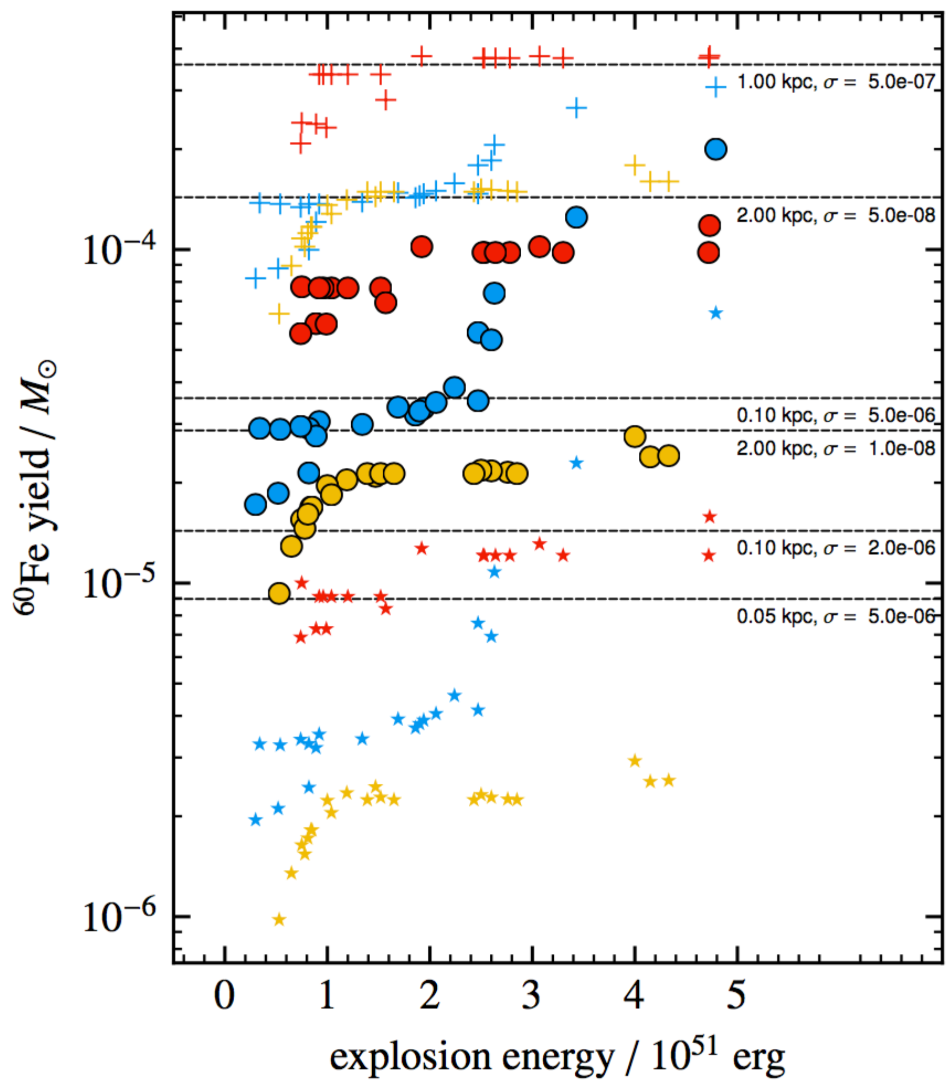
Chemical Evolution

- With half-lives of 7.3×10^5y and 2.6×10^6y respectively, ^{26}Al and ^{60}Fe provide ideal probes of recent star formation in the Milky Way.
- Next generation telescopes will allow us to both increase the number of star forming regions studied in ^{26}Al and include systems studied in ^{60}Fe.
- But I think for this to really be exciting, we need to observe nearby middle-aged supernova remnants (see Jones et al. soon)



Detecting 60Fe and 26Al in individual remnants.



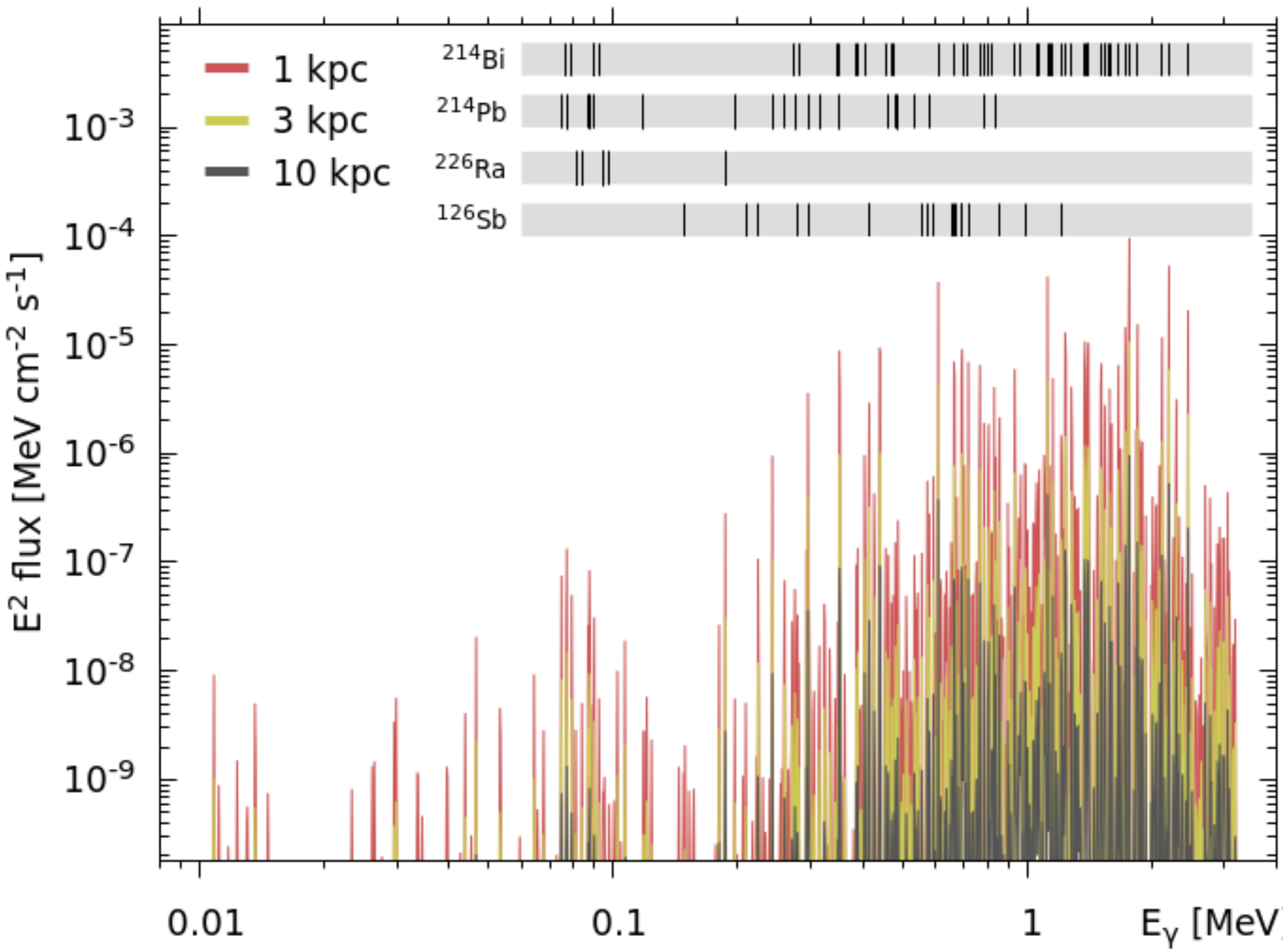


When Opportunity Knocks

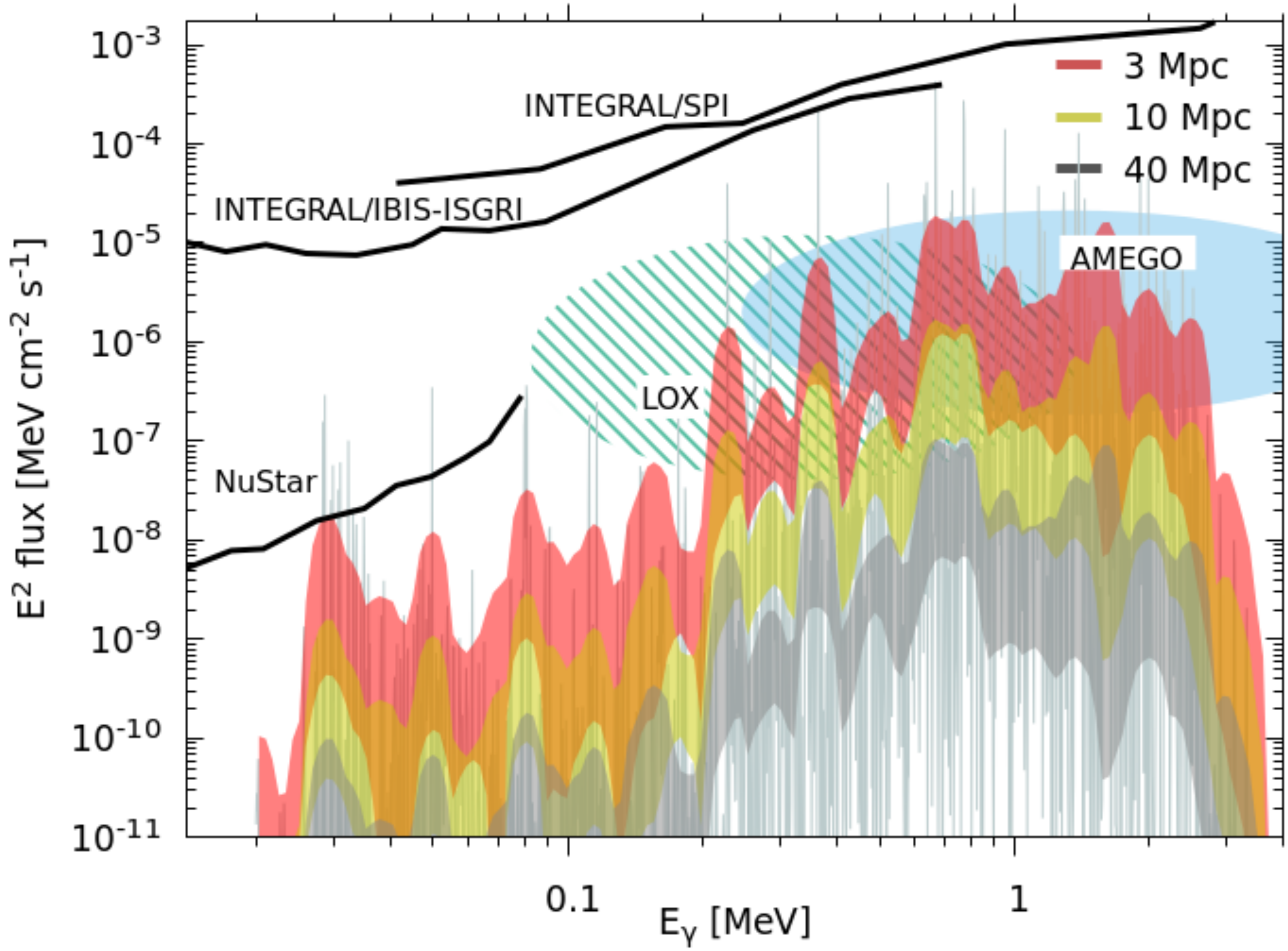
- Galactic Supernovae
  - Will detect ^{24}Na, ^{48}Cr, ^{48}Va, ^{52}Mn, $^{56-57}$Co, $^{56-57}$Ni, ^{43}K, ^{44}Ti, ^{44}Sc, ^{47}Sc, ^{47}Ca, ^{51}Cr, ^{59}Fe, allowing scientists to better probe the neutron fraction in the engine
- Neutron Star Merger:
  - For a really nearby NS merger (3-10Mpc), we can detect gamma-ray lines. We are now determining whether we can truly probe the nature of r-process production (gamma-rays are much more powerful at this than X-ray/optical/UV/IR). New theory studies underway testing the role of nuclear physics uncertainties on the gamma-ray signal.

Probing the details of NS mergers

- NS mergers form a wide range of radioactive isotopes.
- The exact composition depends on the ejecta model and the nuclear physics (can we probe nuclear physics aspects like fission processes with observations of these mergers?)
- The gamma-rays from decay have the potential to probe these detailed yields.

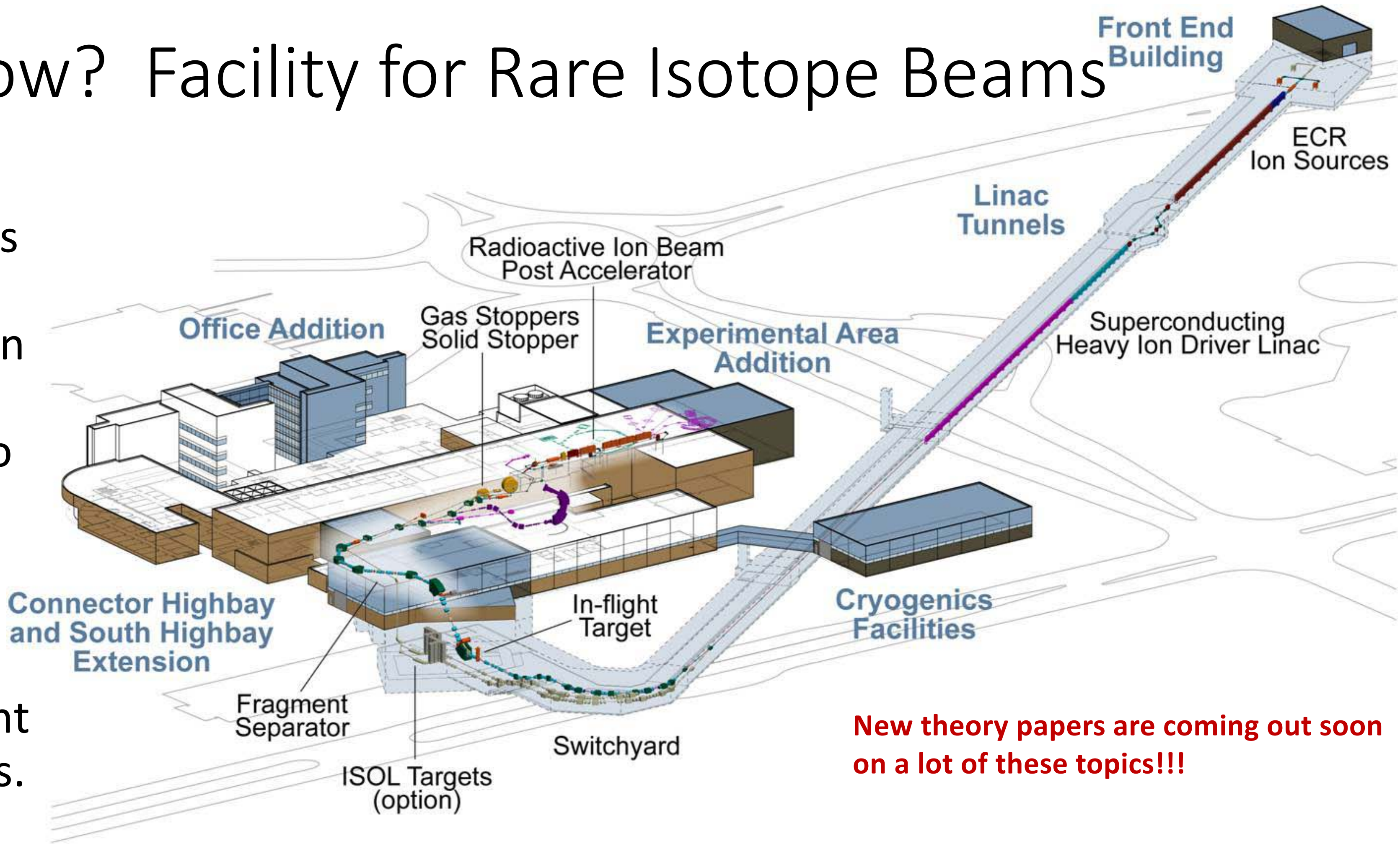


Radioactive nuclei decay and gamma-ray detection of NS mergers.



Why Now? Facility for Rare Isotope Beams

- Nuclear physicists are developing a new facility to measure cross-sections of many important reactions.



New theory papers are coming out soon on a lot of these topics!!!

Why do we care?

- Radioactive decay of ^{56}Ni is the power source behind thermonuclear supernovae. Gamma-rays from the decay process of 56Ni provides a unique window into the distribution of 56Ni – probing the engine and helping us better understand type Ia light-curves.
- Radioactive decay of ^{44}Ti provides a direct window into the core-collapse supernova engine and the observations of Cas A supernova remnant
- 60Fe and 26Al have the potential to probe the star formation history – we need to understand their production first.
- With advances in our understanding of stars, supernovae and nuclear physics, now is the time to advances nuclear astrophysics.